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Are Saturn's rings actually young?

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Spectacular results from Cassini's Grand Finale have provided constraints on the characteristics and evolutionary processes of Saturn's rings. These results have been interpreted as proof that the rings are much younger than the Solar System, dramatically changing our view of the origin of the whole Saturnian system and attracting the attention of scientific media outlets. But we should keep in mind that the age of the rings has not actually been measured (which is impossible per se) but rather is inferred. Here, we put these latest results into perspective and we point out that the young-rings hypothesis has some unsolved problems. Other interpretations, compatible with rings as old as the Solar System, are still possible.

To clarify the debate, it may be useful to start by defining three different ages. First, the ring formation age is the time elapsed from their formation until now. This is the one we wish to constrain. Second, the age of the structures observed in the rings (the Cassini division, various gaps, waves and plateaus) is the time these structures have been present in the rings—a lower bound can be given if the observed structures require a certain amount of time to evolve, and an upper bound can be given by the time it would take for these structures to be erased. For instance, it has been proposed that the Cassini division was created only 10 to 20 Myr ago, in originally smooth (and pre-existing) rings by an inward migration of Mimas[1,2]. Third, the exposure age of the rings is the time they have been exposed to their cosmic environment. On surfaces of airless bodies, the exposure age is estimated by assuming an asteroid or comet bombardment rate and counting the craters per surface unit. On Saturn's rings, this age is given by the duration of meteoroid bombardment needed to pollute and darken the rings and reach the presently observed composition, assuming they were initially made of bright and pure water ice.

Arguments in favour of young rings often rely on young structures or exposure ages[3,4], which are then assumed to date the formation of the rings. As a matter of fact, there is so far no observed structure that would require the rings to be old. Arguments in favour of old rings generally rely on the fact that ring formation takes place early in the history of the Solar System in most formation models—ring structures are then assumed to have appeared recently. But these three ages are actually different concepts, and do not need to be equal. Just as the age of a mountain or a cratered terrain on a planet or moon is not necessarily the age of the planet or moon itself, a structure's age or the exposure age of the rings may actually differ from their formation age: processes erasing the traces of the bombardment (erosion of craters on a planetary surface, or any mechanism that would clean the rings of non-icy material) may disconnect the exposure age from the real age. Below, we briefly review and confront the arguments for old or young rings.

Ring mass and evolution

The first result obtained thanks to the last 22 orbits of Cassini, which plunged between Saturn and the rings, is a measure of the mass of the rings: $M = (1.54 \pm 0.49) \times 10^{19}$ kg, about 0.4 times the mass of the moon Mimas or ~3×10^{-8} times that of Saturn[5]. While it has been used to argue that the rings have a small exposure age (see below), this mass is actually consistent with the expected dynamical evolution of primordial, massive rings. Interactions between the ice blocks that constitute the rings lead to an outward transfer of angular momentum, resulting in the spreading of the rings. This can be modelled by a viscosity in a sheared fluid[6]. As the rings spread, material falls into the planet on one side and goes further away from the planet on the other side. Beyond the Roche radius (about 140,000 km or ~2.4 Saturn radii), the self-gravity of the material wins over Saturn's tidal forces, leading to the formation of moonlets and satellites[7,8]. During this process, the rings lose mass, perhaps even enough to form all the mid-sized moons of Saturn as suggested by their mass–distance distribution[9,10]. As the rings are self-gravitating[11], more-massive rings spread and lose mass faster, so that the mass of the rings converges to an evolution with $M(t) \approx 3 \times 10^{19} \times (t\ /\ 1\ \mathrm{Gyr})^{-1/2}$ kg, whatever their initial mass[12] (Fig. 1, left panel), which gives the mass measured by Cassini[5] after ~4 Gyr. From this dynamical evolution point of view, the measured mass of the rings is fully consistent with their formation at least 2 Gyr ago[13] (Fig. 1, right panel), whereas their initial mass is unconstrained.

Had today's rings been more massive than 2×10^{19} kg, they could not be old, because massive rings evolve fast and don't remain massive for billions of years. Had the rings been less than 10^{19} kg, they could never have been much more massive because it would have taken more than the age of the Solar System to reach such a low mass by viscous spreading. From our present understanding of the viscosity of the rings[6], only the mass measured by the Radio Science team allows the rings both to be as old as the Solar System and to have been initially arbitrarily massive, in agreement with models of their formation[14]. In this case, the present mass would be the natural product of several billion years of evolution, which is appealing[13,14]. Conversely, and admittedly, nothing forbids the rings from having been formed very recently with this mass and having barely evolved since. In terms of evolution, the young-rings hypothesis cannot be tested. In that case, the present mass would be a coincidence, contrasting with the old-rings hypothesis.

Ring mass and pollution

The second important measurement, provided by the Cosmic Dust Analyzer (CDA), is the bombardment flux the rings suffer from micrometeorites. Its value, still unpublished but available from conference proceedings[15], is consistent with pre-Cassini estimates of the

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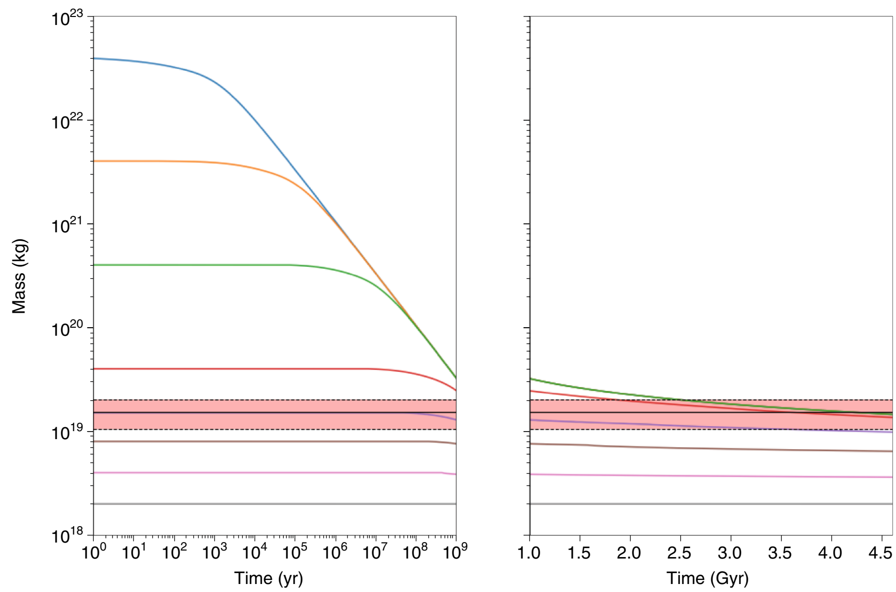

Fig. 1 | Time evolution of the mass of the rings from numerical simulations of their viscous spreading between 60,000 km (Saturn's surface) and 140,000 km (the Roche radius). Each coloured curve corresponds to a different initial mass. Left: the first billion years of evolution with a logarithmic timescale. Right: the subsequent evolution from 1 to 4.5 Gyr with a linear timescale. The black horizontal line shows the mass measured by Cassini[5] and the dashed lines bracketing the shaded region show the uncertainty.

impact flux[16]. This meteoroid material likely contains silicates and organics, and thus should darken the rings. The amount of non-icy material inside the rings was estimated using the radio science instrument[3,17], which is sensitive to the non-icy component in the bulk of the rings. The estimated non-icy material volume fraction ranges from 0.1% to 0.5% in the B ring (the most massive part of the ring system) and up to 6–11% in the fainter, inner-located C ring. Knowing the total mass of the rings, their exposure age can be derived with the ballistic transport model[16], introduced to explain the composition and structure groupings of the rings by the contamination and the impact ejection processes caused by the exogenous micrometeorite flux, with the constraints from CDA. One should keep in mind that this age directly depends on the flux, whose value may be robust, but is not yet finalized. As it stands, because the rings are impressively pure, and not so massive, the exposure age of the rings is found to be a few hundred million years at most[3,5,17]. This timescale received a lot of attention recently and was often presented as the formation age of the rings.

Controversy

On one hand, if the exposure age is equal to the formation age of the rings, one needs some unknown event to create the rings recently—fortuitously with exactly the mass corresponding to the viscous spreading asymptotic mass after ~4 Gyr of evolution. For theorists and Solar System modellers, this is difficult: the Solar System is thought to have been mostly quiet since the giant planets' instability[18,19], which is thought to have occurred at least 3.9 Gyr ago[20], and probably even longer ago[21,22].

On the other hand, if the rings are as old as the Solar System while the exposure age is shorter, one needs some mechanism that disconnects the exposure age and the formation age to make old rings look young. Without invoking an unknown mechanism of destruction or removal of the pollution that would keep the rings clean forever (however, see below), one could imagine that some unknown event triggered a recent increase in the bombardment rate of the Saturnian system, so that the measured rate is not representative of the history of the Solar System. For theorists, this is also very difficult to explain.

Whether the rings are old or young, something seems to have happened recently in the Solar System, but what? No one firmly knows, but it is important to understand that there is no reason a priori to choose between an unknown recent ring formation event and an unknown recent bombardment intensification event, and to firmly conclude that the rings are either old or young. In contrast to some claims, there is no consensus in the ring community. Arbitrary ad hoc variations of the bombardment rate are as unlikely as an arbitrary ad hoc recent formation of $(1-2) \times 10^{19}$ kg rings. How to solve this conundrum?

A difficult recent formation

There have been valuable attempts at providing scenarios for a recent ring formation. Dynamical arguments suggest that Tethys and Dione have not crossed their 2:3 mean motion resonance, whereas it should have been crossed if they were older than a hundred million years[23]. Hence, it has been proposed that two pre-existing Saturnian satellites (a proto-Rhea and a proto-Dione), excited by the Sun's evection resonance near eight Saturnian radii, suffered a catastrophic collision recently. The debris of this destructive impact would then have scattered across the Saturnian system, down to the Roche limit, and given birth to the present system, including the rings, not more than one hundred million years ago[23]. However, only a small amount of mass could have reached the Roche limit, and the outcome of such a collision would simply be re-accreted into one or a few moons, likely leading to satellite surface rejuvenation[24]. A dynamical geophysical model of Saturn's mid-sized moons[25] finds that Mimas must be younger than ~1 Gyr if Saturn's rings were present first, but the inferred timescales depend on the assumed history of Saturn's dissipation factor. By contrast, model ages for densely cratered terrains on the mid-sized moons are ~4 Gyr (ref. [26]). Analysis of the amorphous to crystalline ice ratio inside Rhea's Obatala crater allowed the age of this crater to be estimated to be 450^{+110}_{-130} Myr (ref. [27])—this constrains Rhea to be older than that. Similar, ongoing studies of Dione are driving towards similar conclusions with the age of, for instance, the Entellus crater estimated to be 600 ± 240 Myr (ref. [28]), so that more recent formation of these two moons, and the rings, seems difficult.

Maybe Tethys and Dione had a more complex migration history, avoiding the 2:3 resonance, possibly because the efficiency of the tidal push from Saturn can depend on the considered satellite[29].

A collision between a differentiated satellite twice as massive as Mimas and a ~20 km comet could produce a cloud of icy debris that would generate the rings, while leaving the original satellite as Mimas[30,31]. Such a collision could happen at any time, including recently—a recent study[31] estimates the chances for this to happen within the last few hundred million years to be 1%. This scenario works if the progenitor satellite is orbiting close to the outer edge of today's rings at the time of the impact. But such a configuration is very unlikely, or at most, fleeting, as Saturn's tides would have pushed away the satellite on a timescale much shorter than the age of the Solar System. It could be kept there by a chain of resonances with Enceladus and Tethys[31], but only assuming the tidal dissipation within Saturn to be very low, which is at odds with recent conclusions published by two teams from Jet Propulsion Laboratory (USA) and Institut de Mécanique Céleste et de Calcul des Ephémérides (France). With the tidal dissipation they report[32], the chain of resonances is broken in 0.6 Gyr at most, ruling out a recent occurrence of this scenario.

To date, despite these interesting possibilities, there is no fully satisfactory scenario explaining recent formation of the rings. If they are old, how can they have a young exposure age?

The rings can appear younger than they are

Beyond the provocative idea that the exposure age is actually very uncertain because the value of the bombardment rate is not yet published, and that key parameters such as the yield and the efficiency with which extrinsic bombarding material retains its absorptive properties are almost unknown, one could invoke various processes in the physics of the rings and of the impacts of micrometeorites that may scramble the estimation of their formation and exposure ages.

The first and most obvious solution is that the bombardment rate varies in time, and that the rate measured today is exceptionally high. Since the size distribution of small Kuiper belt objects is often assumed to be in steady state as the result of a collisional cascade[33], the drift rate of the smallest bodies of this reservoir should also be steady. Nonetheless, events such as the one that gave birth to the ancient Haumea family[34] certainly lead to spikes in the dust production rate. Could an event of this kind have occurred just a few million years ago, biasing our flux estimate? Considering the evolution and variety of the various micrometeorite sources inferred from CDA measurements at Saturn (Kuiper belt objects, but also Centaurs and possibly Jupiter-family comets)[35,36], the exogenous mass influx at Saturn may not be constant in time.

A more crucial point is that the exposure age is equal to the formation age if and only if the rings are a closed system that does not lose material to the outer world. This is clearly not the case. First, they spread. Acting as a conveyor belt, the rings carry into Saturn, or beyond the Roche limit, the pollution they receive, together with their icy content. In an evolution like the one shown in Fig. 1, a third of the accumulated dust mass is lost. In other words, if the rings were more massive in the past, the pollution was dissolved in more ice than the mass measured today, resulting in a lower fraction of non-icy material than naively expected. This is not negligible, but would not change the order of magnitude of the exposure age, especially considering that the Kuiper belt was more massive too, hence the pollution rate may well have been, on average, higher in the past.

Second, another striking result of Cassini's Grand Finale is the finding of solid grains between the planet's atmosphere and the rings, and of organics in the upper atmosphere. Nanograins have been detected by the CDA, and the modelling results suggest they mostly originate from the B and C rings—50% and 40% respectively[37]. Among the 636 grains of known composition, a third are of silicate type, and only two thirds are of water type. In terms of mass, the measured ice to silicate ratio is 2 to 11, contrasting sharply with the average ring composition (>95% ice by mass). One possible explanation is that the (unknown) process responsible for the erosion of the rings and the launch of these nanograins is actually 'cleaning' the rings, preferentially removing silicates rather than water ice. These results vividly illustrate that dark material is constantly lost from the rings. To account for the observations, 1,800–6,400 kg s^{-1} need to be excavated from the rings in the form of nanograins, 18% of which fall into Saturn[37]. Putting all these numbers together, one finds between $1,800 \times 0.18 / 11 = 30$ and $6,400 \times 0.18 / 2 = 600$ kg of silicates falling into Saturn from the rings every second. In one hundred million years, that is between 10^{17} and 2×10^{18} kg, respectively 0.6% and 12% of the total mass of the rings, enough to evacuate all of the silicates present in the rings now!

In the same spirit, "a plethora of organics" has been found in the upper atmosphere of Saturn, close to the ring plane, by the Cassini Ion and Neutral Mass Spectrometer[38]. This was unexpected because these heavy species should diffuse down towards the centre of Saturn. The observed abundances can be explained by an inflow of material from the rings estimated between 4,800 and 45,000 kg s^{-1}, a fourth of which is composed of water, a fifth of CO or N_2, and the rest (more than half) of organics[38]. Again, this is enough to evacuate all of the organics present in all of the rings in roughly a million years. In other words, if we define the cleaning time as the time needed to wipe away all the silicates and organics presently found in Saturn's rings, it is shorter than the exposure time.

Admittedly, the observed molecules are most likely coming from the faint D ring, which must then be replenished by the C ring[38]. One could, however, suppose that the C ring is somehow similarly replenished in organics by the B ring, in order to sustain the observed flow. In addition, the colour of the small moons closest to the rings has recently been attributed to the accretion of a reddish chromophore coming from the rings[39], hence the rings seem to lose non-icy material also towards the outside of the system. From the above considerations, it seems likely that the non-icy material is efficiently evacuated after it is brought to the rings by micrometeoroid bombardment. It is also suggested that ice particles from the E ring diffuse inwards and hit the small moons and the rings, so that "contamination of Saturn's rings by bright icy particles or water vapour offers counterevidence to previous arguments that the observed brightness of the rings indicates recent formation"[39]. Hence, the exposure age may not be directly converted to the formation age of the rings. These numbers even open the possibility that the rings were formed less icy than they are today and are cleaned faster than they are polluted!

Discussion and conclusions

In summary, to our knowledge and understanding of the rings' structures and processes, there is no constraint that forces the rings to be old. But with the still mysterious but potentially efficient ring-cleaning process observed at play, the link between the exposure age and the formation age is broken, so that one also cannot conclude that the rings formed "around the age of the dinosaurs"[40–42].

The discoveries from the Grand Finale are so rich and amazing that much work remains to be done to fully understand the chemical evolution of the rings, in particular how and why so much non-icy material is evacuated. The physics of the hypervelocity impact of a micrometeorite on an icy block is not well constrained by models or experiments. The fate of nanograins in the environment of Saturn is complex and may depend on their composition, potentially changing the ice to silicate ratio on the way to Saturn.

We should also humbly admit that lots of physics governing the ring evolution and transport processes is not well known. It has recently been suggested that the rings are losing material at a rate that would make them disappear in less than 820 Myr (ref. [43]). Even if the future fate of the rings is a separate topic from their origin, this may change our understanding of their evolution, as they could have been more massive in the recent past, and evolve faster than in viscous models that ignore this ring rain. However, about 90% of this flow comes from the C ring, so its sustainability and its influence on the evolution of the massive A and B rings is so far not clear.

Lastly, one might also imagine that the lighter rings have a different origin and age than the more massive ones, which are the focus of this paper. All in all, the numbers we have for now suffer from uncertainties that are too large to draw definitive conclusions. All one can say it that it is very likely that the rings are not a closed system, as demonstrated many times by the Cassini results, which means that the interpretation of their exposure age should be taken with care and not simply equated to their formation age.

Because the young-rings hypothesis does not explain why the measured mass is precisely the viscous asymptotic mass of 4.5-Gyr-old rings, here we take the liberty to push back to the forefront the idea that the rings formed concurrently with Saturn despite their young appearance, as suggested by models of their formation and evolution[12–14,30,31].

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Author contributions

A.C. initiated and coordinated this work. S.C. ran the simulations and produced the figure. All of the authors contributed to the planning and writing of the manuscript.

Competing interests

The authors declare no competing interests.

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